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Research Paper

Realistic evaluation of crop water productivity for sustainable farming of wheat in Kamin Region, Fars Province, Iran

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ABSTRACT

Currently, the economic wheat production faces severe challenges due to an increasing number of droughts. In an effort to enhance yields, most arid and semi-arid areas increase the water volume used for irrigation and cultivation of wheat, resulting in an intensified pressure on water resource systems. Therefore, it has become increasingly important to determine the required water volume per unit area in relation to expected wheat performance. However, such an estimation of relevant performance factors has been difficult due to unpredictable water supply capacities and the lack of reliable estimates for the demand of water. The potential crop water productivity (PCWP) defined in this study was comparing with its actual value has which obtained from field measurements based on a new approach of risk quantification. Using this comparison of water use, the management coefficient was estimated, and the production reliability of wheat was calculated.

Based on these factors, farms that had competently adapted their management in line with climate change and water availability were selected. The results reveal that only 26 of a total of 666 wheat farms which evaluated for this case study have had reliable crop water productivity and could thus be used as models for other farms. The results showed 100% increasing in CWP with a 27% reducing in hydro-module on these farms, in which case more than 34% will be reduced the groundwater withdrawal. Therefore, the sustainability of groundwater resources would be better, whereas the benefit cost ratio of the whole region and the superior farms has no significant difference. The amount of water that these farms use and the resulting yield can be a suitable reference to determine the expected yield and required water volume per unit area.

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1. Introduction

Intensifying agriculture to increase the food supply of the ever-growing population with only an economical and income focused point of view has been creating excessive pressure on environmental resources. This pressure has especially been raised due to climatic changes, associated with an increase of droughts in arid and semi-arid regions. These phenomena lead to soil degradation, increase soil and water salinity and as a result compromise the regions agricultural stability (Gao et al., 2017). Therefore, it is necessary to determine sustainable conditions for stable crop and agricultural production. It is worth mentioning that quantifiable indicators are essential to assess stable conditions.

Since measuring the intricate situation of any agricultural system is a very complex endeavor, agricultural sustainability is not precisely measurable (Pretty, 1995). Acquisition and integration of spatially and temporally significant and thus suitable indicators, is a general problem in the assessment of farming practices. To predict system trends, it is necessary to select suitable and specific indicators (Pretty and Thompson, 1996; Brandi et al., 2017).

The efficient operation and management of an irrigation system plays an important role in the sustainability of irrigated agriculture (Kumar and Singh, 2003; Kam and Ding, 2017). Crop water productivity (CWP) is a measure for the performance of irrigation systems and describes the efficiency of the physical system and operational decisions that deliver water from a water source (Irmak et al., 2011). Reliable evaluation of crop water productivity is necessary to improve system management (Small and Svenddsen, 1990; Clemmens and Molden, 2007), to determine the overall state of the system (Bhadra et al., 2010; Pereira et al., 2012) and to detect the

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elements that cause problems in the water resource system (Vos, 2005; Shakir et al., 2010).

To quantify the gap between potential and actual crop water productivity, it is necessary to strategically compare the farm and global crop water productivity. This calls for a quantification of the vulnerability of the water resources system (Diwekar, 2017). Most studies in the arid and semi-arid area have been focusing on the utilization of soil and water resources (Liu et al., 2001; Arfanuzzaman and Rahman, 2017). Few studies focused on water sufficiency, while providing a soil suitability analysis (Wang and Lou, 2001). Evaluating farming practices with an interdisciplinary approach that encompasses environmental, economic and socio-institutional aspects is relatively new; and also, limited efforts have been made to evaluate farming practices via location-specific indicators and their thresholds.

CWP is a function of many diverse factors such as atmospheric water vapor pressure deficit, soil fertility, irrigation, and pest and disease control. Any management factor that increases crop yield (including economical aspects) also increases CWP, making it less responsive to changes in these factors, than yield (Liu et al., 2007). However, how to improve water productivity is a rather complex question, given the agronomic, hydrologic, and socio-economic conditions of the arid and semi-arid area (Deihimfard et al., 2007).

Climate change affects water resources and crop productivity and farmers cannot adapt their management strategy accordingly. As a result, the physical and chemical properties of water and soil are often transformed. Consequently, CWP is not the same for all farms and can even change annually. The CWP value for each farm is calculated by dividing the measured yield per unit of available water. These two factors possess strong spatial and temporal variability and are the reason that CWP has been an obscure value with a range of variation created by climate change and farm management. This unpredictability needs to be considered and modeled when CWP is applied as an indicator.

Similar to the definition of sustainability by Tamara and Francesco, CWP could be defined as an appropriate practice of natural resources by considering present and future resource consumption (Menichini and Rosati, 2013). Thus, energy producers (such as farms) need to generate integrated performances and balance between economic and environmental lines to satisfy inter-generational equity needs (Modaresirad et al., 2017).

Our study introduces an approach to assess the reliability of on farm crop water productivity, which is essential for identifying key issues to improve water management. Here, we compare the potential CWP with actual values obtained from field measurements. This comparison of unpredictable conditions is based on a novel approach to quantify hazard and leads to a management coefficient of water use that is useful to understand the behavior of the farmer, while taking general agricultural trends into account. Analyzing the results leads to insights into potential improvement methods and enable the development of water management policies that enable planners to improve the sustainability of water resources systems.

Evaluation of the reaction of individual farmers to improve the sustainability of water resources systems would be ideal, but is not easy because of time and investment limitations (Hua et al., 2016). Classification of farmers to homogenous groups of farm-types and evaluation of the reaction of each farm-type instead of individual farmers is a way which can be used for solving this problem. Our study attempts to enhance our understanding of the factors for differences in agricultural productivity and sustainability. The main objective was to assess the performance of irrigated wheat farms with a focus on the analysis of cross-sectional differences of CWP and to determine the potential productivity in the Kamin Region, Fars Province, Iran. We used a data base of 666 irrigated wheat farms located in this region to develop a model to simulate the spatial distribution of yield and the quantifying hazard for the use of available water.

In the classification of farms based on soil and water characteristics, the difference in yields in each class is significant, but the range of variations in each class is not the same in the whole region. On the other hand, the mean of each class has a significant difference and indicates the role of the basic production factors in yield. But in this study, there is a view point that due to the management of farmers, in each class where water and soil conditions are the same, there is a significant difference in yield. Hence, the management coefficient we introduced in this study can show the role of these factors on sustainable water use. It is worth noting that the difference between locally and globally calculated values of CWP could be caused by the changing climate of recent years. Due to climate change, the water volume has been receding and irrigation has been increased to maintain production. Therefore, management plays a role in increased productivity in recent years. Weakness of production management caused intensification of resources pressure and yield sustainability.

1.1. Reliability and hazard quantification

Risk quantification is the next step following problem formulation and the analysis of different uncertainties that potentially cause a risk of failure (risk identification). Quantifying risk is of key importance in agriculture because simulation, prediction and engineering design are all based on quantitative rather than qualitative concepts (Ganoulis, 2009; Mishra et al., 2012). By definition, risk analysis relates to uncertainties and any quantification of risks should be based on methodologies that take uncertainties into account. Two main theoretical approaches are available for doing so: (i) the probabilistic approach and (ii) the fuzzy set theory. When loads and resistances are assumed to be constant at a given time, static reliability analysis is considered first.

Although, such a stochastic approach is relatively well established, fitting probability laws and analyzing dependencies between random variables needs large quantities of data, which are not always available. If load and resistance are assumed as independent, direct integration may be applied to quantify risk and reliability. Available data may be used to estimate extreme values and risk of accidents, such as the hydrologic risk and management behaviors.

In the present study, we consider loads and resistances to be time-independent, positive scalars, applied on a single component of a system. Time-independency is a necessary assumption that enables direct integration for risk quantification. This approach is generally known as static reliability analysis.

Unsteady system or reliability should be considered in situations where loads and resistances vector with several components. On-farm production with unsteady resources is also a system with several management components. Therefore, the reliability of agricultural systems under hazard should be evaluated using the stochastic approach.

Here, we consider the load or exposure λ as a random variable L. In this case uncertainties are associated with an estimation of L and are quantified via probabilistic methods. The resistance or capacity r is expressed with the same unit as exposure. In uncertain cases, probabilistic methods may be used to describe resistance as the random variable R. If both λ and r are positive random variables and probabilistic methods are utilized to quantify risk (Fig. 1), we can compute the risk pF as follows:

$$pF = p(L \geq R) = \int_0^\infty F_R(l) f_L(l)\, dl \quad (1)$$

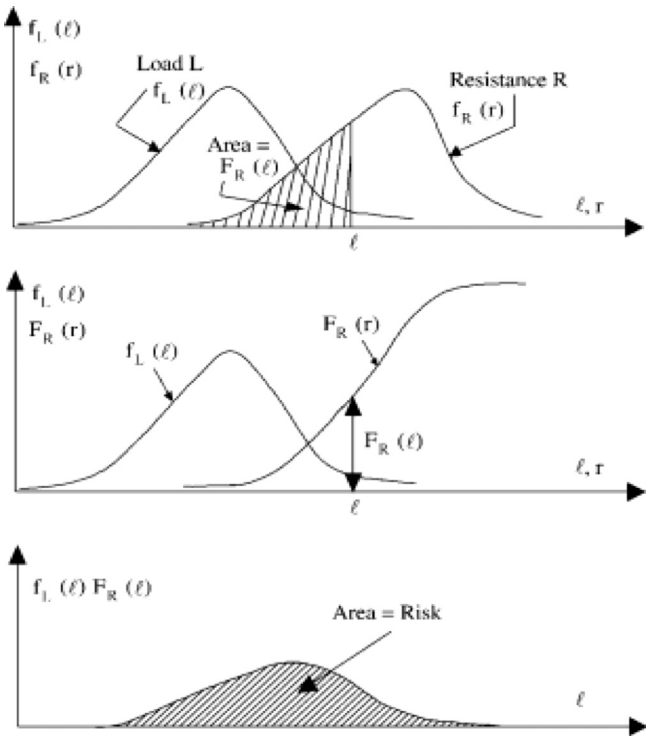

Fig. 1. Direct quantification of risk via probability distribution functions.

1.2. Potential crop water productivity

Crop water productivity is an important measure to understand water-food relationships. Moreover, this provides a basis for the assessment of system sustainability. CWP combines the physical accounting of water with the resulting yield or economic output to indicate the value of a unit of water as:

$$CWP = Y/ET \quad (2)$$

Here, CWP is the crop water productivity in kg m^{-3}, Y is the crop yield in kg ha^{-1}, and ET is the seasonal evapotranspiration in m^3 ha^{-1}, which can be assumed to be the consumptive water use.

However, traditional methods are not sufficient to estimate CWP on a global scale, while including large spatial and temporal variations across different geographical locations. Liu et al. (2007) developed and tested a simulation model to estimate wheat (*Triticum aestivum* L.) yield and CWP. They obtained good agreement from a comparison, simulating yields and FAO statistical yields in 102 countries over a total of 10 years. Simulated yield and reported CWP follow a linear regression:

$$CWP = 0.16 * Yield + 0.4 \quad (3)$$

$R^2 = 0.8788$ $P < 0.01$

In their study CWP values ranged from 0.160 kg m^3 in Rwanda to 1.887 kg m^3 in Ireland (Liu et al., 2007). Many factors that affecting plant growth, such as water vapor pressure deficit of the atmosphere during the growth period of the crops, the availability of water when it is most needed, soil fertility, application of fertilizer, and general climatic conditions caused differences in observed CWP. Estimated yield and CWP values can be calculated via the following equation:

$$CWP = 0.18 * Yield + 0.2 \quad (4)$$

$R^2 = 0.7859$ $P < 0.01$

Faramarzi et al. (2010) studied irrigated wheat yield (Y) and consumptive water use (ET) using an uncertainty analysis at several locations in Iran. Simulated Y and ET were used to calculate crop water productivity (CWP) via the following equation:

$$CWP = 0.13 * Yield + 0.09 \quad (5)$$

$R^2 = 0.64$ $P < 0.01$

The different values for CWP have been informed by global scale (Liu et al., 2007) and local scale (Faramarzi et al., 2010) reinforcing that using certain values of CWP that are based on a given value of yield is challenging; thus, potential values of CWP for each farm have a range of variability and consequently no fixed reference for CWP. Uncertainty methods should be applied to compare a farm's actual and potential CWP. Therefore, a farm's CWP can be computed using the following equations:

$$r_1 = 0.18y_k + 0.2; r_2 = 0.16y_k + 0.4; r_3 = 0.13y_k + 0.09$$

Here, y_k = yield per ton per ha on the kth farm in the present study.

As a result, we defined a set of CWP values for each given value of yield with the mean ($\bar{r}_k$) and standard deviation (σ_k):

$$(CWP)_k = \bar{r}_k = \frac{1}{n_r}\sum_{i=1}^{n_r} r_i \quad (6)$$

$$\sigma_k = \sqrt{\frac{1}{n_r}\sum_{i=1}^{n_r}(r_i - \bar{r}_k)^2} \quad (7)$$

Here, r_i is the estimated value of CWP, resulting from the above equations ($n_r = 1,\ldots,N_r$ and $N_r = 3$) for the kth farm ($k = 1,\ldots,N_k$) of total farms ($N_k = 666$).

According to Eq. (1), the probability function for each farm's set of CWPs is required, which we consider as a resistance function in that equation. Supposing a normal variable distribution in each set, the distribution and its function can be developed as follows:

$$f_{R,k}(r) = \frac{1}{\sigma_k\sqrt{2\pi}} e^{-(r-\bar{r}_k)^2/2\sigma_k^2} \quad (8)$$

$$F_{R,k}(r) = \int_{-\infty}^{r} f_{R,k}(z)\,dz \quad (9)$$

Thus, the potential value of CWP for any given value of yield is located within this uncertainty range. This value compares to CWP, which calculated by dividing crop production per available water volume (actual CWP). The yield value of each farm had a potential CWP value ($\bar{r}_k$) with an uncertainty range (σ_k), which we use to calculate risk and reliability (1-pF) in this approach.

1.3. Actual crop water productivity

We computed the actual value of CWP based on the yield of each farm and the available water volume calculated according to Eq. (2). Although the crop water productivity is an uncertain value in here, it is an important indicator and could also be used to evaluate a farm's sustainability. Hence, it is necessary to analyze this uncertainty and determines the variability range of CWP based on the role of effective factors. The hydro-module of consumptive water use, yield and resulting CWP is affected by crop production, soil types, and electrical conductivity of irrigation water use (EC) and the volume of available water, thus all of these values need to be monitored and utilized to calculate a farm's CWP.

We calculated the hydro-module (h_k) by dividing the available water volume per farm area (Lit/sec-ha). We estimated by yield (y_k) dividing crop production per farm area (Ton/ ha). We calculated crop water productivity (l_j) by dividing crop productivity per the volume of available water (Kg/M^3) and defined $j = 1,\ldots,N_j$ as the class number.

We classified electrical conductivity, soil type, and yield based on a Mont-Carle method, classifying each of these using three classes (Low, Normal and High) over their variability range. E.g., we shaped 27 classes in this study and we defined the variability ranges of CWP in each class ($N_j = 27$). Each class (j) describes a set of farms and we assigned the calculated value of CWP to each farm. We applied observed values of yield and water availability to calculate the CWP for each farm (l_k), which is affected by soil type, EC, and yield factors. Each class has maximum, medium, minimum, and the range of a farm's CWP.

Due to the effects of unpredictable factors on crop production, we created each class range based on the farm's soil, yield, and water salinity. Assuming a normal distribution for the probability function of each class of CWP, we consider a load function in Eq. (1) and develop it as following:

$$f_{L,j}(l) = \frac{1}{\sigma_j\sqrt{2\pi}} e^{-\left(l_k-\bar{l}_j\right)^2/2\sigma_j^2} \tag{10}$$

Here, the calculated CWP of each farm is $\bar{l}_j$ and the variation range of its class is σ_j, and they can be computed via the following equations:

$$(CWP)_j = \bar{l}_j = \frac{1}{n_j}\sum_{k=n_{j-1}+1}^{n_j} l_k \tag{11}$$

$$\sigma_j = \sqrt{\frac{1}{n_j}\sum_{k=n_{j-1}+1}^{n_j}\left(l_k - \bar{l}_j\right)^2} \tag{12}$$

1.4. Management coefficient

To evaluate production sustainability on each farm, it is necessary to determine by how much the CWP value can increase. This value may be defined as the potential value of CWP and can be used as a reference point for each farmer providing an estimate for similar yields for corresponding soil and water properties. Usually, the CWP value is calculated as yield per water use and is a function of soil, water, climate and practical management on each farm. Many studies tried to estimate the CWP value based on impact parameters for wheat crop production as well as describing several models to present relationships between CWP and yield values.

E.g. a farm that used 5660 m^3 of water and produced three tons of wheat per hectare has a crop water productivity of 0.53 kg/m^3. An analysis of referencing values revealed that the crop water productivity could range between 0.8 and 1.2 with this level of wheat production (Liu et al., 2007).

Defining potential values of CWP and their range is inaccurate; it is not a meaningful indication value, and it is only a reference point for comparing farms. However, dividing CWP's obtained for each farm per the potential values will be the basis for calculating management coefficient (MC) as following:

$$MC_k = \frac{l_k}{\bar{r}_k} \tag{13}$$

This indicator will quantify the used resource efficiency in the field. Furthermore, the management coefficient variations can be utilized to evaluate production sustainability. The farm with the highest value of MC is the best farm, though compared to other farms it does not have the highest value of yield or the maximum amount of CWP. This farm competently adapted management methods as a response to climate change and water availability.

Fig. 2. Study location in southern Iran.

2. Material and methods

2.1. Study area

The study area is located in the Kamin Region in the Fars province, Iran, has a geographical area of 1754 km^2 and a semi-arid climate regime (Fig. 2). Average rainfall is 280 mm with a maximum of 519 mm and a minimum of 152.5 mm. Total farmland is 40,000 ha with 22,000 ha of farms and 600 ha of gardens, irrigated with groundwater resources between 2014 and 2015. Over 95% of all groundwater resources are withdrawn to cover the water demand of agriculture.

We randomly selected a subset of the irrigation districts with a total area of 7000 ha. For each district, we collected the observed data of one or several adjacent wheat farms. The area of these selected districts was about 30% of the total irrigated land. The monitored zones were a subunit of the collected data and we assumed that the obtained results can be generalized for the entire farmland via geo-statistical methods.

2.2. Effective parameters on uncertainty of crop water productivity

2.2.1. Land suitability

Land suitability evaluation looks for key production in the region including wheat, alfalfa, maize and barley, covering a total area of 30,000 ha. Based on semi-detailed soil studies in this region, we defined two soil families and eight soil series in two physiographic units. We determined physiological requirements of each crop via described rated-base methods.

For our qualitative evaluation, we used land and climatic characteristics along with the growing crop needs, based on the means of simple limitation and parametric method (Stories and Root Square Method). The obtained indexes for barley, wheat and alfalfa were higher than those for other crops. Restrictive parameters on crop productivity in the region included soil physical properties, such as carbonate contents, soil salinity, and drainage along with climatic variables. The variation ranged from 0 to 100, demonstrating the value of each parameter. We calculated the land suitability index for wheat yield by multiplying values as follow: If the index is between 70 and 100, the land is suitable (S1); If it is between 50 and 75, the land is relatively suitable (S2); If it is between 25 and 50, the land is lightly suitable (S3); If it is between 0 and 25, the land is unsuitable, with the unsuitable classification to suitability potential (N1) and any suitability potential (N2).

In this study, we define the key word "Soil Unit" to represent the land suitability index for wheat at each farm and extend its values to the whole region via geo-statistical methods (Kriging approach) as

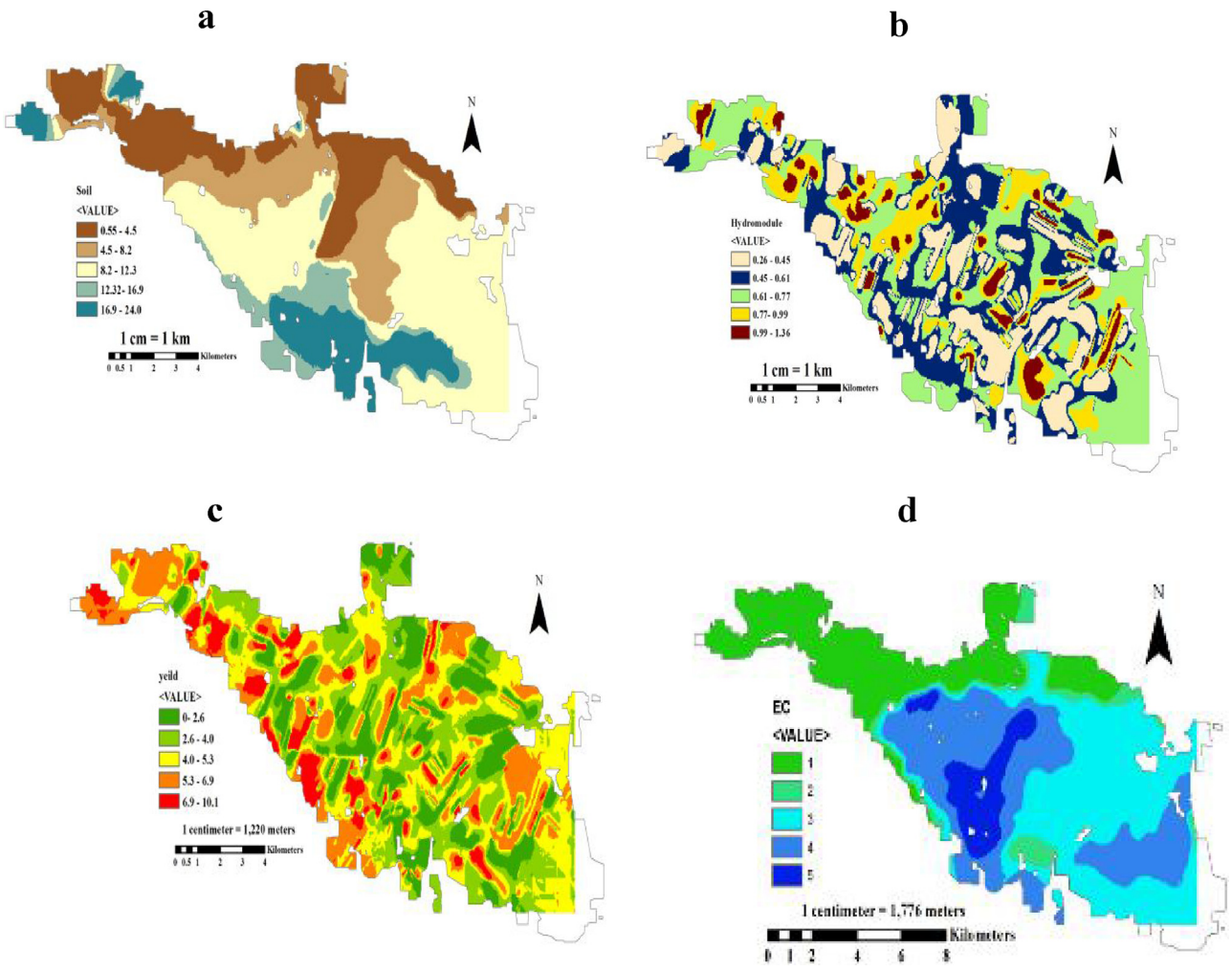

Fig. 3. Spatial variations of soil texture (a), hydro-module (b), yield (c), and salinity of water use (d) based on geo-statistical analysis and measured data.

shown in Fig. 3-a. Based on the qualitative evaluation of land suitability; soil texture that disables wheat production extends from the southern to central flat plain and expected yields are low. However; suitable soil classes are situated in northern to central parts and their yields were expected to be better in comparison.

2.2.2. Available water and water quality

Recent droughts as well as the use of uncontrolled groundwater sources have caused a significant drop of the groundwater level in most plains of Iran such as the Kamin plain and as a result, this region faces a new challenge of water restriction. As a result of the water crisis, accurate estimations of crop water requirements, gross irrigation requirements, hydro-module and the volume of groundwater pumping are essential. However, this is not possible without accurate estimations of irrigation efficiencies in each plain.

When more than ET water used is considered, the term irrigation efficiency is used to define the effectiveness of the irrigation system in delivering all the water beneficially used to produce the crop. Irrigation efficiency is defined as the ratio of the volume of water that is beneficially used to the volume of irrigation water applied. Water losses that occur as a result of excessive deep percolation, runoff, weed ET, wind drift, and spray droplet evaporation are normally not considered as beneficial uses, and thus tend to decrease irrigation efficiency. A major problem with using irrigation efficiency as a performance parameter is the subjectivity involved in the definition of beneficial use. Most irrigation systems in Kamin are operated primarily to supply water for crop ET, which allows water application efficiency and irrigation efficiency to be used interchangeably. Other factors that impact beneficial uses and, thus, irrigation efficiency are local water regulation agency allocation rules and farmer-practiced irrigation management strategies. The overall irrigation efficiency represents the efficiency of the entire physical system and operating decisions in delivering irrigation water from a water supply source to the target crop. It is calculated by multiplying the efficiencies of water conveyance and water application (Irmak et al., 2011).

In the Kamin plain, we selected several farms according to the level of implemented under-pressure irrigation, the total irrigated area of cultivation, and the kinds of irrigation method (traditional or modern system). We determined available water and irrigation efficiency based on a field survey and farm measurements of several irrigated districts. We measured quantity and quality of water use (withdrawn from wells) in selected farms. Based on measurement values and the geo-statistical method (Simple Kriging approach), we modeled the spatial distributions of water quality and quantity and depict the results in Fig. 3-d and b.

According to the different levels of crop cultivation (specially crop-pattern), we calculated the annual hydro-module by dividing the water use volume by farm size during growing season, defined as lit/sec-ha. Here, farms hydro-module has changed from 0.26 to 1.36 and its distribution is shown in Fig. 3-b.

Then, we extended the hydro-module spatial variability to the whole region using the geo-statistical method (Simple Kriging approach) and depict the results in Fig. 3-b. Our results reveal that

Table 1
Sample results of our geo-statistical analysis to find the spatial distribution of the basic parameters of crop production.

Prediction Errors	Soil unit	Hydro module	Water EC	Yield
Samples	666	666	666	666
Mean	−0.014	−0.02	−0.01	−0.02
Root–Mean–Square	2.10	2.07	2.13	2.08
Mean Standardized	−0.004	−0.01	−0.001	−0.01
Root–Mean–Square Standardized	0.97	1.01	0.97	1.02
Average standard Error	2.14	2.02	2.17	2.02

only in a small part of this region, hydro-module was more than 1.0 lit/sec-ha. But, for most parts of the region hydro-module was smaller than 0.8 lit/sec-ha. Also, we calculated the hydro-module for each month with a maximal value in July and with an amount of 1.3 lit/sec-ha.

We measured electrical conductivity (EC) of the irrigated water of selected farms as a water quality index. The spatial variation of EC in the region was 0.5–5.2 (ds/m^2). By using Simple Kriging approach, we modeled and expanded these variations to the whole region (Fig. 3-d). EC fluctuations matched the land suitability results but did not show any consistent trend in relation to yield.

2.2.3. Spatial variability of yield

All factors affecting the uncertainty of crop water productivity also had an effect on yield. We applied the yield to determine CWP as a management coefficient and to assess the crop production of each farm and the resulting resources sustainability. Therefore, determining the relationship between variations in yield and these factors is necessary to evaluate the range of CWP.

As a result, we made an effort to find the spatial relationship between yield and the factors mentioned (water salinity, soil unit, and hydro-module) with geo-statistical simulation methods like Co-Kriging. For all cases, we calibrated with reasonable accuracy but we found no significant relationship between the measured values of yield and the results of simulation models in the validation phase (Fig. 3-c).

We tested the relationship between yield and the factors mentioned via multivariate regression and curve fitting methods, but without obtaining acceptable results. To summarize, we were not able to obtain a significant relationship between yield and salinity, soil unit, and hydro-module variables.

3. Results

We measured land suitability, water use quality and quantity, and yield for each farm within the data collection areas. We simulated the yield results based on the geo-statistical method (Kriging approach) as shown in Fig. 3-c. The amount of yield changed from 1 to 10 tons per ha throughout the different parts of this study. Comparing results for the spatial variation model of farm yield and soil classification revealed that the distribution of yield did not match land suitability patterns. We observed the highest yields on the southern flat plains (10 tons per hectare), while land suitability was not a very good fit for wheat production. To find a perfect correlation coefficient between yield and soil unit, we used and failed approaches like curve fitting and Disjunctive Co-kriging (geo-statistical method), and ultimately, we did not find a model to describe the correlation (Table 1).

Subsequently, we assumed that the volume of available water could be the reason for differences between land suitability and observed yields. A spatial variability comparison of yield and hydro-module showed a small relationship between these factors. Hence, we utilized multivariable regression and curve fitting approaches to investigate these issues. As a result yield had an improved relationship with hydro-module compared to the soil unit. However, the result was not significant.

Next we considered the spatial relationship between the electrical conductivity (EC) of the water, the hydro-module of the available water and soil, considering yield via multivariable geo-statistical methods such as Disjunctive Co- Kriging. All of the calibration results of the model were acceptable but we observed many differences between measured and estimated yields in the validation process.

Finally, we concluded that no significant correlation existed between the spatial variation of yields and the water quality and quantity. Due to soil salinity, some areas in the sample region were not suitable for wheat production. However, the land suitability of these areas could be improved by the quality of irrigation water. Thus, it seems that the main yield variations could be affected by imprecise factors such as farm management (Abolpour et al., 2006; Abolpour and Javan, 2007; RazaviToosi and Samani, 2016).

Therefore, we evaluated the effect of these factors on yield via water use efficiency indicators, such as crop water productivity. The range of CWP as an indicator to classify farms needs to be explained. The maximum and minimum amount of CWP obtained in the study area has been creating the variation range used to classify the farms.

Based on a Monte Carlo approach, we placed the variation ranges of yield, soil texture and water salinity in the region on three classes for each of these factors, and created 27 classes of their fluctuations as a result (Table 2). We calculated potential and actual values of CWP of farms from Eqs. (6) and (11) and illustrated average and standard deviation for each class in Tables 2 and 3. The results were used to calculate the reliability and risk based on Eqs. (8)–(10).

Climate change, cultivation management and water amount affect CWP, thus changing it over time even in a same area. For that reason, maximum and minimum values of CWP observed in the study area were neither certain nor deterministic and they changed in different conditions. However, when the actual CWP is lower than the potentially possible value, farmers over-impacted the water resources to achieve more yields at the cost of future sustainability of production in this region. Therefore, potential values of CWP and the corresponding range could be defined as production sustainability indicator.

Similar to Liu et al. (2007) and Faramarzi et al. (2010) we used the following equation to calculate the uncertainty range of CWP. The equation was developed based on measured yield and water use from each farm obtained from real data rather than estimated data.

$$CWP = 0.1 * Yield + 0.1 \quad (14)$$

$R^2 = 0.69 \quad P < 0.01$

Although increasing water use causes also increases crop production, crop water productivity may subsequently be reduced. Each crop needs enough water to increase production as long as the crop water productivity does not reduce. Determining the expected performance and required water volume per unit area has therefore become vitally important. However, a reliable determination of water demand is difficult due to the role of other production factors in performance and even more so due to unstable and uncertain conditions for the estimation of water supply capacity.

Therefore, it is necessary to define the optimal point of water use in this condition. We illustrate this point in Fig. 4, where risk and performance curves intersect. In addition, the curves of lower and upper limits of our risk and performance predictions are depicted in Fig. 4 ($\alpha = \pm 0.01$). We located the optimal condition within the area of hydro-module (from 0.33 to 0.63) with an optimal value of 0.44 lit/sec-ha. In this optimum rage, we obtained values of 12% to 38% for risk and 62% to 88% for performance. Based on the results

Table 2
Average values for potential and actual crop water productivity, and results of risk quantification analysis for each class.

Class Soil-Ec-Yield	Hydro L/Sec/ha	Yield Ton/ha	Risk%	Performance%	Upper Kg/M^3	Middle	Lower	σ_k	$(CWP)_k$	$(CWP)_j$
1-1-1	0.66	2.48	82.33	67.67	0.80	0.65	0.41	0.19	0.62	0.32
1-1-2	0.68	2.75	82.96	67.04	0.84	0.70	0.45	0.20	0.66	0.33
1-1-3	0.65	2.88	82.38	67.62	0.86	0.72	0.46	0.20	0.68	0.36
1-2-1	0.53	2.56	86.37	63.63	0.81	0.66	0.42	0.20	0.63	0.34
1-2-2	0.60	2.63	84.21	65.79	0.82	0.67	0.43	0.20	0.64	0.33
1-2-3	0.62	2.33	82.11	67.89	0.77	0.62	0.39	0.19	0.60	0.31
1-3-1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1-3-2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1-3-3	0.53	2.56	78.10	71.90	0.81	0.66	0.42	0.20	0.63	0.37
2-1-1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2-1-2	0.78	5.59	85.66	64.34	1.29	1.21	0.82	0.25	1.11	0.57
2-1-3	0.74	5.29	84.76	65.24	1.25	1.15	0.78	0.25	1.06	0.57
2-2-1	0.58	5.26	75.90	74.10	1.24	1.15	0.77	0.25	1.05	0.71
2-2-2	0.58	5.38	77.82	72.18	1.26	1.17	0.79	0.25	1.07	0.71
2-2-3	0.57	5.48	86.89	63.11	1.28	1.19	0.80	0.25	1.09	0.67
2-3-1	0.67	5.22	83.61	66.39	1.23	1.14	0.77	0.25	1.05	0.60
2-3-2	0.83	5.93	79.12	70.88	1.35	1.27	0.86	0.26	1.16	0.63
2-3-3	0.51	4.46	74.12	75.88	1.11	1.00	0.67	0.23	0.93	0.65
3-1-1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
3-1-2	0.87	8.52	92.27	57.73	1.76	1.73	1.20	0.32	1.57	0.72
3-1-3	0.76	7.86	82.59	67.41	1.66	1.62	1.11	0.30	1.46	0.85
3-2-1	0.57	7.81	68.43	81.57	1.65	1.61	1.10	0.30	1.45	1.16
3-2-2	0.49	8.24	67.40	82.60	1.72	1.68	1.16	0.31	1.52	1.29
3-2-3	1.00	8.65	99.66	50.34	1.78	1.76	1.21	0.32	1.59	0.57
3-3-1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
3-3-2	0.61	7.66	76.21	73.79	1.63	1.58	1.09	0.30	1.43	1.00
3-3-3	0.72	8.04	87.36	62.64	1.69	1.65	1.13	0.31	1.49	0.84

Table 3
Standard deviation of potential and actual crop water productivity, and results of risk quantification analysis for each class.

Class Soil-Ec-Yield	Hydro L/Sec/ha	Yield Ton/ha	Performance%	Upper Kg/M^3	Middle	Lower	σ_k	$(CWP)_k$	$(CWP)_j$
1-1-1	0.36	0.95	12.70	0.15	0.17	0.12	0.02	0.15	0.20
1-1-2	0.31	0.89	15.91	0.14	0.16	0.12	0.02	0.14	0.22
1-1-3	0.33	0.71	16.30	0.11	0.13	0.09	0.01	0.11	0.19
1-2-1	0.15	0.92	9.21	0.15	0.17	0.12	0.02	0.14	0.15
1-2-2	0.25	0.90	12.71	0.14	0.16	0.12	0.02	0.14	0.19
1-2-3	0.30	0.80	13.92	0.13	0.14	0.10	0.01	0.13	0.19
1-3-1	NA	NA	NA	NA	NA	NA	NA	NA	NA
1-3-2	NA	NA	NA	NA	NA	NA	NA	NA	NA
1-3-3	0.20	0.79	15.66	0.13	0.14	0.10	0.01	0.12	0.22
2-1-1	NA	NA	NA	NA	NA	NA	NA	NA	NA
2-1-2	0.30	0.69	17.32	0.11	0.12	0.09	0.01	0.11	0.35
2-1-3	0.32	0.85	17.44	0.14	0.15	0.11	0.02	0.13	0.30
2-2-1	0.29	0.66	18.21	0.11	0.12	0.09	0.01	0.10	0.29
2-2-2	0.26	0.75	17.70	0.12	0.14	0.10	0.02	0.12	0.32
2-2-3	0.19	0.66	12.07	0.11	0.12	0.09	0.01	0.10	0.17
2-3-1	0.28	0.76	17.45	0.12	0.14	0.10	0.02	0.12	0.29
2-3-2	0.47	0.45	25.25	0.07	0.08	0.06	0.01	0.07	0.47
2-3-3	0.20	0.36	18.62	0.06	0.06	0.05	0.01	0.06	0.28
3-1−1	NA	NA	NA	NA	NA	NA	NA	NA	NA
3-1-2	0.23	1.02	12.49	0.16	0.18	0.13	0.02	0.16	0.43
3-1-3	0.34	0.81	19.18	0.13	0.15	0.11	0.02	0.13	0.47
3-2-1	0.36	1.05	20.49	0.17	0.19	0.14	0.02	0.16	0.52
3-2-2	0.24	0.81	19.75	0.13	0.15	0.11	0.02	0.13	0.49
3-2-3	0.14	1.06	0.07	0.17	0.19	0.14	0.02	0.17	0.15
3-3-1	NA	NA	NA	NA	NA	NA	NA	NA	NA
3-3-2	0.31	0.84	18.67	0.14	0.15	0.11	0.02	0.13	0.42
3-3-3	0.27	0.49	15.27	0.08	0.09	0.06	0.01	0.08	0.37

presented in Fig. 4, risk increases and performance decreases when the hydro-module was raised as following:

$$Risk = \alpha_r - \left(\frac{\beta_r}{H}\right) \quad (15)$$

$$Perf = \alpha_p + \left(\frac{\beta_p}{H}\right) \quad (16)$$

Where $\alpha_r = 65$ and $\alpha_p = 35$, $\beta_r = \beta_p = 17$ and H is the hydro-module by lit/sec-ha ($P < 0.01$). We obtained these equations based on a curve fitting analysis and the results are shown in Table 4.

We calculated the management coefficient by dividing the CWP of each farm by the potential values (Eq. (13)) and extended its spatial variability to the whole region via geo-statistical methodology (Simple Kriging approach). The results for this are shown in Fig. 5. Comparing these results between the distribution maps of yield, soil class, and quantity and quality of water use (Fig. 3) and the results of management coefficient distribution (Fig. 5) revealed

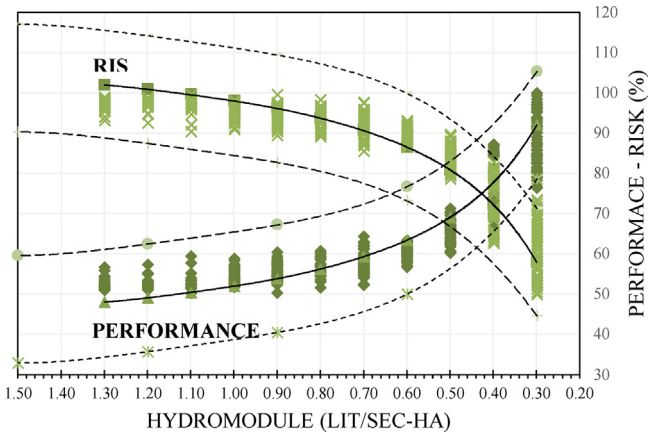

Fig. 4. Optimal value of water use in uncertain conditions based on risk and performance quantifications.

Table 4
Curve fitting analysis results of our risk and performance data.

Equation	Risk	Performance
Correlation Coefficient	−0.9487	0.9486
R–squared	89.99	89.99
R–squared (adjusted for d. f.)	89.98	89.98
Standard Error of Estimate	5.17991	5.18016
Mean absolute error	4.16391	4.1639948
Dubrin–Watson statistic	1.3995	1.39948
P–Value	0.00	0.00
Lag 1 residual autocorrelation	0.299861	0.299873

that MC variations did not match the spatial distribution patterns of these factors. However, the MC distribution map reveals a clear pattern and this region can be divided into two parts: one with good management and another with poor management. Because of this, it seems that groupie management or "Colony Farmers" is the main reason affecting MC variations.

As a consequence, each colony needs a groupie manager who is a leader and provides a pattern for the other farmers. Fig. 6 shows the farms with optimal performance, improved crop water productivity and high probability for yield. In these farms, 26 of a total of 666 wheat farms, had a hydro-module of 0.44 lit/sec-ha, crop water productivity ranging between 0.7 and 1.00 kg/m^3 and a probability of high wheat production of more than 70%.

Comparing the results of Figs. 5 and 6 shows that the colonies are located according to these farms. As a result, they competently adapted their management methods with climate change and water availability. Finally, these farms were sustainable farms and their yield and water use can be used as a suitable reference to determine expected yield and required water volume per area unit.

Some of the production factors on the superior farms were compared with other farms (Table 5). Comparing the mean values showed that except hydro-module of water use and CWP, other factors don't have significant changes with the superior farms. The comparison of minimum each factor was similar to the above case but in maximum, the differences were significant. For example, the maximum area of farms was 70 ha in the region, but it was 17 ha in the superior farms (Table 5). Therefore, the farms lower than 20 ha have the better adaptation with the fluctuations of water resource capacity.

Other factors which can have the role in superiority of these farms are the suitable irrigation duration based on the chemical and physical characteristic of soil and the farm level. The irrigation duration more than 36 days was observed in this region, whereas it was 10 days for superior farms (Table 5). It can be concluded that complying the irrigation duration and farm level, has a role in improving management efficiency and creating optimum conditions in the farmland.

The maximum depth of groundwater level was 90 m around the superior farms, but it was 125 m on the other sites. In the superior farms, the maximum withdrawal of groundwater resources was less than 20 lit/sec and it was observed more than 30 lit/sec on the other sites (Table 5). Therefore, one of the major achievements of the superior farms modeling is sustainability of groundwater resources, in which case the reduction in groundwater withdrawal will be more than 34%.

The maximum of irrigation efficiency was 57% in the superior farms, whereas 67% was also observed for irrigation efficiency in the region, but they were being out of the category of superior farms (Table 5). Therefore, opinion of increasing irrigation efficiency to create superior farms is not correct. The maximum of crop production was 10 tons per hectare in the region, but in the superior farms were produced 9 tons per hectare on the maximum conditions (Table 5). Therefore, it is observed that the choosing superior farms is not only due to increase in production. Sometimes in order to increase the production, water use has increased and it has been approved, when CWP of top farms were compared with others. The CWP's mean of superior farms and other farms were equal 1 and 0.54, respectively; which is about 100% increase in CWP (Table 5).

But considerable matter is that the superior farms merely because the increase in CWP were not selected. For example, in the region was also observed the CWP more than 2, but these farms were being out of the selected group by the here model presented. The reason for this is that it has no enough credit in comparison with the CWP's region potential and also it was outside of the limitations boundary of uncertainty conditions. It may be only in specific circumstances and probably happened for one year. Therefore, because of high risk of acquiring this CWP, these farms omitted in the model. This issues also observed, when the minimum and the standard deviation of CWP's superior farms were compared with the others. For example, the CWP's range of superior farms was 0.7–1.5 with 0.2 standard deviation, but it was 0.3–2.14 with 0.4 standard deviation in the region (Table 5). Therefore, it seems that superior farms had proper CWP with the high reliability and a lesser amount of risk.

The variable range of the benefit per cost of the whole region and the superior farms has no significant difference. According to result, water management and production type in superior farms has no more cost for farmers but also increase their farms income so it seems that this type of water use management and crop produce would be better for them (Table 5). Comparing hydro-module is showed to reduce 27% between 0.47 of superior farms with 0.64 of other farms (lit/sec). Based on the results, it is confirmed that due to comply the different sustainable aspects on superior farms including production factors, economic and social issues, they had achieved to stability conditions.

4. Conclusion

For a specific yield, the calculated values of crop water productivity decreased one-to-one from Eqs. (3) to (5) and 14. E.g., according to the average yield in the region of about 5 tons per hectare, calculated values of CWP were 1.2, 1.1, 0.74 and 0.6, respectively. Comparing these values indicated that the crop water productivity in this region was nearly half of the normally expected values. Since the yield was kept constant in our calculations, the result can only be explained by additional water use.

We conducted this study, to find the spatial distribution models for yield, quality and quantity of water use, and land suitability index using geo-statistical analyses. Furthermore, via multivari-

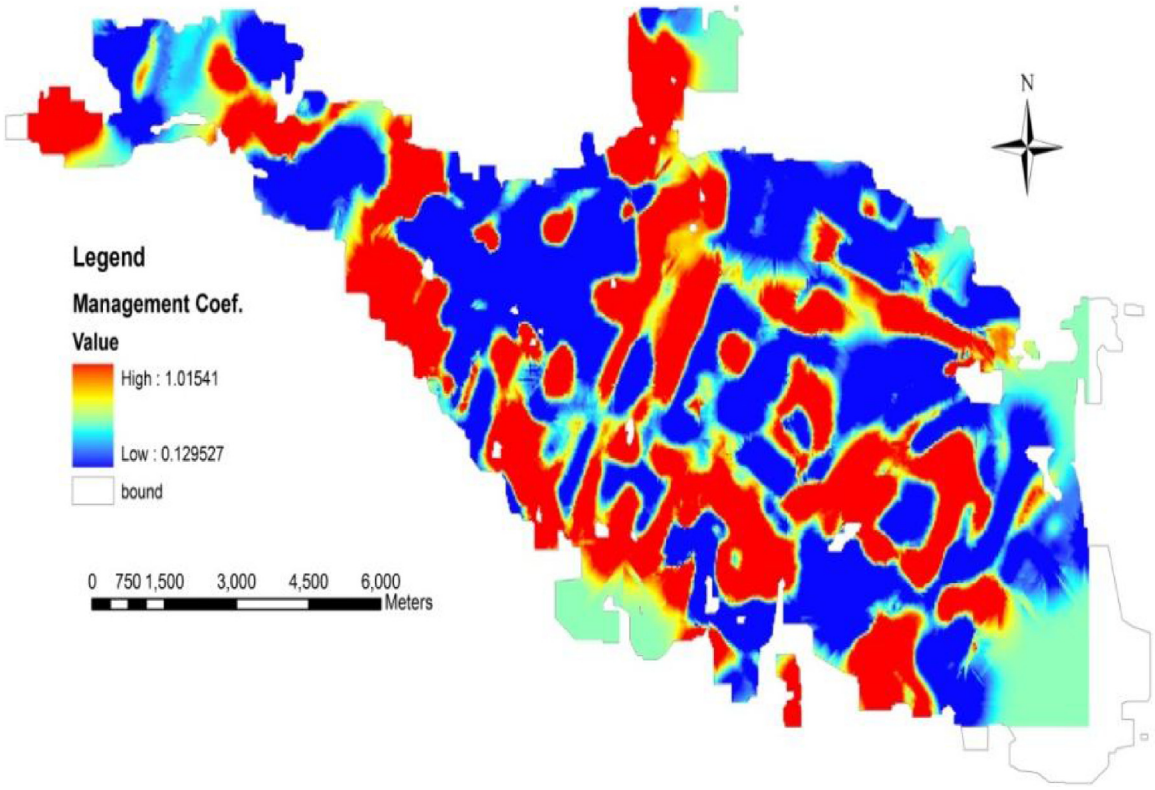

Fig. 5. Spatial distribution of management coefficient for wheat production and water use in the Kamin Region.

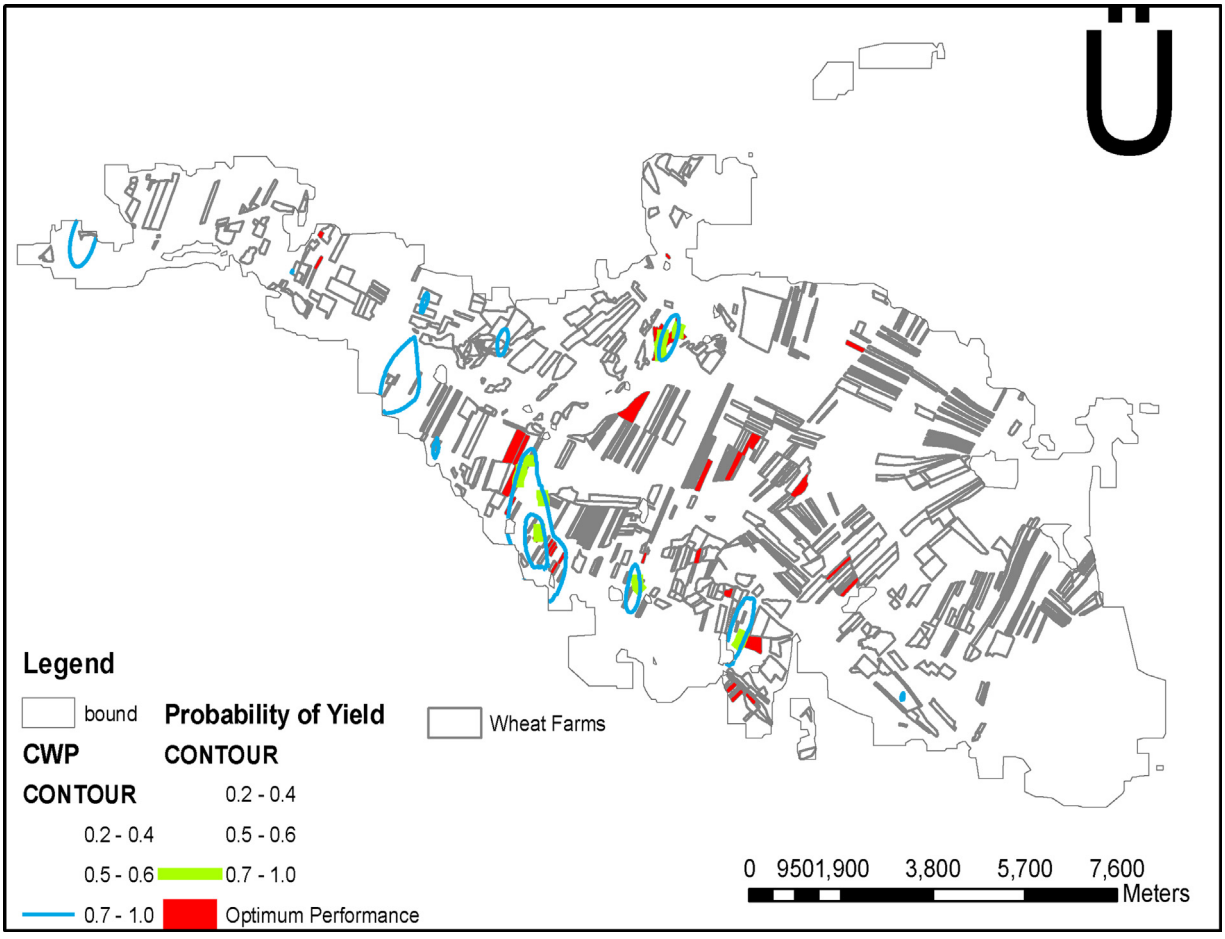

Fig. 6. Selection of sustainable farms that produce wheat based on optimum performance, improved crop water productivity and high probability of yield.

Table 5
Comparing the characteristic of superior farms with other farms.

Items	Total Farms				Superior Farms			
	Max	Min	Mean	Std[a]	Max	Min	Mean	Std
Farm level (ha)	70.01	0.74	4.01	6.30	17.21	0.74	3.84	4.91
Irrigation duration (days)	26	1	5.57	6.18	10	1	5.04	2.78
Well depth (m)	125	20	55	26.1	90	20	50	21
Well discharge (lit/sec)	30	3	12.41	7.95	20	3	11.14	8.32
Irrigation efficiency (Frac.)	0.67	0.30	0.35	0.07	0.57	0.30	0.36	0.08
Hydro-module (L/s-ha)	1.30	0.30	0.64	0.29	0.50	0.45	0.47	0.02
Benefit cost ratio	2.19	1.01	1.32	0.15	2.19	1.15	1.41	0.22
Yield (Ton/ha)	9.99	1.00	4.48	2.26	8.96	1.05	4.51	2.67
Crop water production (Kg/M^3)	2.14	0.30	0.54	0.38	1.50	0.70	1.00	0.20

[a] Standard deviation.

ate regression, curve fitting and geo-statistical methods, we tested the relationship between yield and mentioned factors but did not obtain a satisfactory result. Not only were the spatial variations of these parameters not simulated but also the spatial classifications of these parameters were not zoned clearly (Fig. 3). However, the management coefficient variations were simulated with a spatially classified separate zone (Fig. 5). Therefore, it seems that the effects of management by the farmer towards a sustainable production were more significant than other basic production factors such as soil, water and climate change. Groupie management or "Colony Farmers" could affect this management.

Hence, the management coefficient we introduced in this study can show the role of these factors on sustainable water use. It is worth noting that the difference between locally and globally calculated values of CWP could be caused by the changing climate of recent years. Due to climate change, the water volume has been receding and irrigation has been increased to maintain production. Therefore, management plays a role in increased productivity in recent years. Weakness of production management caused intensification of resources pressure and yield sustainability.

Our results indicate that wheat farms could reduce risk by $25 \pm 13\%$ by adopting best practices of efficient farms. Deficiency of irrigation water and poor land quality are two fundamental constraints to increase reliability by $75 \pm 13\%$ in the region. Because of subsidies such as seed, fertilizer and credit, the produced wheat is costlier than other crops and continually causes change in cropping patterns. The results of suggested analysis could create a sustained cropping pattern through effective management and additional investments in both land and water resources.

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